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Heat-Storing Medium

Background

The invention relates to a heat-storing medium for a low-temperature range, to a regenerator for low-temperature refrigerators, and to a low-temperature refrigerator.

Low-temperature refrigerators are usually multistage gas refrigerators with the aid of which temperatures in the range below 15 Kelvin can be generated. Such gas refrigerators operate according to various principles, for example according to the Gifford-McMahon, the Stirling or the pulse tube principle. Independent of the operating principles, these refrigerators have in common that they comprise, in the area of a so-called cold head between the hot side and the cold side, a volume through which a working fluid flows, said volume being filled with the heat-storing medium and referred to as regenerator. The working fluid flows alternately in both directions through the regenerator and serves as an intermediate storage for heat absorbed or dissipated by the working fluid. The regenerator thus serves for thermally separating the working fluid in the cold chamber from that in the compressor-side hot chamber. For this purpose, the regenerator must have as high a heat capacity as possible as compared with the fluid flowing through the regenerator. While for temperatures of up to 15 Kelvin high-grade steel, bronze, lead or other metal bodies can be used, this is not possible at temperatures lying considerably below the aforementioned temperature since the specific heat capacity of these metals as compared with that of helium drastically decreases as from 30 Kelvin and below, and approaches zero in the range below 5 Kelvin. Therefore, in very low temperature ranges, i.e. in the range below 15 Kelvin, a fill of rare earth compounds is used as heat-storing medium in the regenerator, as is, for example, described in ~~EP-A-0 411 591~~US 5,186,765. A drawback encountered when using rare earth compounds is their magnetism which poses a problem when the compounds are employed in strong magnetic fields, for example in magnetic resonance tomographs. Further, rare earth

compounds are susceptible to oxidation, tend to break due to their partial brittleness when vibrations occur, and are expensive.

Helium and other low-boiling gases are also suitable storing media for very low temperature ranges. For example, helium has, in the range below 15 Kelvin, a high specific heat capacity with a pressure-dependent maximum at approximately 9 Kelvin, thus in this temperature range said heat capacity lies far above the heat capacity of metals. From DE-A-199 24 184 a regenerator is known in which helium is used as a heat-storing medium, wherein helium, like in a heat exchanger, is stationarily stored in a helically wound tube or a tube bundle in the regenerator housing. Alternatively, the regenerator housing may be filled with helium as the storing medium, while the working fluid flows in tubes through the regenerator housing.

Tests on regenerators of such a configuration showed however that a targeted temperature of 4.2 Kelvin cannot be reached, which is due to the high heat input from the metallic helix and tube material and the too small contact surface.

US-A-4,359,872 describes a fill composed of helium-filled glass spheres as heat-storing medium. The wall thickness of the glass spheres must be relatively large to present an adequate strength at the required internal pressure and the low temperature.

It is an object of the invention to provide a heat-storing medium with a high heat capacity in a very low temperature range, a regenerator and a low-temperature refrigerator comprising a heat-storing medium with a high heat capacity for very low temperatures.

~~According to the invention, this object is achieved with the features of claims 1, 10, 11 and 12.~~

Summary

The heat-storing medium according to the invention destined for a low-temperature range, i.e. for temperatures below 15 Kelvin, is composed of a set of gastight sealed hollow bodies which is permeable to the working fluid, wherein each hollow body comprises a fill of low-boiling gas as heat-storing medium. Low-boiling gases are gases with a boiling point below 30 Kelvin. This holds true, e.g., for the gases hydrogen, helium and neon, and in fact to all their isotopes. Low-boiling gases have by their nature a relatively high specific heat capacity at low temperatures and are thus well suited as storing medium at temperatures below 30 Kelvin. Low-boiling gases are relatively inexpensive and may be enclosed in a hollow body comprising a hollow body wall of non-magnetic, mechanically suited, non-oxidizing and inexpensive material. The heat-storing medium can thus be constructively adapted, in terms of its chemical, mechanical and magnetic properties, to any use thereof. Further, as compared with tubes and/or helices, the gastight sealed hollow bodies offer a considerably larger surface via which the heat exchange is effected. This considerably promotes the heat transfer.

Preferably, the storing medium is a hollow body helium fill. A helium fill is a fill with a helium isotope, for example, with ^3He or ^4He. The storing medium helium has a relatively high specific heat capacity at temperatures below 15 Kelvin and is thus well suited as a storing medium at temperatures down to the range of 2 Kelvin. Further, helium is obtainable at a low price.

Preferably, at a temperature of 4 Kelvin the helium fill has a pressure of more than 0.5 bar (7.25 psi), in particular a pressure above the critical pressure. At a helium fill pressure of more than 0.5 bar an absolute heat capacity is realized which allows the produced heat quantities to be stored in a relatively small regenerator. Such a regenerator is of very compact configuration as compared with metallic heat accumulators.

Preferably, the material and the wall thickness of the hollow body wall are selected such that the thermal penetration depth equals at least once the wall thickness. The thermal penetration depth μ is represented by the following equation

$$\mu = \sqrt{2\frac{a}{f_{mod}}}$$

wherein a is the temperature conductivity of the selected hollow body wall material at the working temperature (for example, 2 Kelvin), and f_{mod} is the modulation frequency at which the working gas cyclically alternately flows through the heat-storing medium. The working frequency f_{mod} shall be assumed to amount to 1.0 to 10.0 Hz for low-temperature refrigerators.

The wall of the hollow body is made of metal. Metals and metal alloys offer a good heat conductivity and good mechanical properties, which allow a small hollow body wall thickness to be realized. The hollow body wall can be made of copper, aluminium, silver, brass, steel or other metals or metal alloys. Alternatively, the hollow body wall can be made of ceramic material.

By selecting non-ferromagnetic metals as material for the hollow body wall, a heat-storing medium can be provided which is suitable for use in strong magnetic fields, for example, for use in magnetic resonance tomographs and the like, without the need to take any further measures.

According to a preferred embodiment, each hollow body has a diameter of less than 3.0 mm. At diameters of less than 3.0 mm a set of hollow bodies has such a large volume-specific surface that a sufficiently rapid heat absorption or dissipation is ensured. Typical diameters range from 0.2 to 0.7 mm.

Preferably, each hollow body is of approximately spherical configuration. Selection of the spherical shape ensures, in the fill composed of hollow bodies, an approximately constant defined ratio between the hollow body surface, overall hollow body volume and fill material volume across the overall fill material volume.

A regenerator according to the invention comprises a housing which is filled with the heat-storing medium described above. A low-temperature refrigerator according to the invention comprises the aforementioned regenerator and is configured as a regenerative cycle, preferably as a Gifford-McMahon, Stirling or pulse tube refrigerator, wherein helium is used as a working fluid. Thus helium is used both as a storing medium and, separately, as a working fluid.

Still further advantages of the present invention will be appreciated to those of ordinary skill in the art upon reading and understanding the following detailed description.

Brief Description of the Drawings

~~Hereunder an embodiment of the invention is described in detail with reference to the figures in which:~~

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of illustrating the preferred embodiments and are not to be construed as limiting the invention.

Fig. 1 shows a schematic representation of a refrigerator,

Fig. 2 shows a sectional view of a refrigerator regenerator with a fill composed of a set of helium-filled hollow bodies, and

Fig. 3 shows a sectional view of a helium-filled hollow body.

Detailed Description

Fig. 1 schematically shows a refrigerator 10 comprising, ~~as essential components,~~ a compressor 12, a regenerator 14 and an expansion chamber 16 including a cold head. The compressor 12 as well as the regenerator 14 and the expansion chamber 16 are interconnected by lines 18,20.

The compressor 12 compresses and, if necessary, precools a working fluid, preferably helium. Subsequently, the compressed working fluid flows through the gas line 18 and through the regenerator 14 where it dissipates heat to a heat-storing medium contained in the regenerator 14. The working fluid continues to flow to the expansion chamber 16 where it is allowed to expand. The cooling working fluid absorbs, in particular via a cold surface, heat from the surroundings, and is subsequently returned through the line 20 to the regenerator 14. When the working fluid flows through the regenerator 14, it absorbs heat stored in the heat-storing medium, and is returned through the line 18 to the compressor 12. The regenerator 14 serves as a thermal insulation between the compressor 12 and the expansion chamber 16.

The refrigerator 10 can be configured as a Gifford-McMahon, Stirling or pulse tube refrigerator, it can however generally operate in any other regenerative cycle, wherein a regenerator 14 is used for the purpose of intermediate storage of heat in a low-temperature range. A low-temperature range covers temperatures between 0 and 15 Kelvin.

The regenerator 14, a longitudinal section of which is shown in Fig. 2, is essentially composed of a cylindrical ~~of~~ or oval housing 24 at whose transverse-side housing walls 26,27 the lines 18,22 end. The regenerator housing 24 contains, as a heat-storing medium, a set 22 of pourable and gastight sealed hollow bodies 30, which is gas-permeable to the working fluid. The regenerator 14 can be filled homogeneously or in layers with various layers of different heat-storing media.

All hollow bodies 30 have approximately the same size and are of approximately spherical configuration. The fill can further be composed of a mixture of hollow bodies with various diameters. The hollow body wall 32 is made of copper or any other metal or metal alloy, and has a thickness of approximately 0.2 mm or less. The diameter of a hollow body 30 ranges from 0.2 to 2.0 mm, but may be larger, but not larger than 3.0 mm. The hollow body 30 is gastight sealed and contains a helium fill 34. At room temperature, the helium fill 34 has a pressure of approximately 200 bar (2900 psi), and at a temperature of 4 Kelvin a pressure of several bars. The hollow bodies 30 containing the helium fill 34 may, for example, be produced by a manufacturing process in which drops of the molten hollow body wall material flow through a helium gas-filled cooling chamber. The hollow body fill can be composed of a single helium isotope or a mixture of different helium isotopes or of isotopes of hydrogen or neon or a mixture of the aforementioned elements. The material for the hollow body wall, the modulation frequency at which the working gas alternately flows through the regenerator, as well as the wall thickness of the hollow body must be selected such that the penetration depth μ equals at least once the wall thickness. The penetration depth μ is represented by the following equation

$$\mu = \sqrt{2\frac{a}{f_{mod}}}$$

wherein a is the temperature conductivity of the selected hollow body wall material at the working temperature (for example, 4 Kelvin), and f_{mod} is the modulation frequency at which the working gas cyclically alternately flows through the heat-storing medium. The working frequency f_{mod} shall be assumed to amount, for example, to approximately 1.0 Hz for low-temperature refrigerators.

The heat-storing medium composed of the gastight sealed and helium-filled hollow bodies 30 has a high absolute heat storing capacity in a small volume

in particular in the very low temperature range of less than 15 Kelvin due to the high specific heat capacity of helium in this temperature range. By selecting a suitable metal for the hollow body wall 32, the heat-storing medium can be optimally adapted, in terms of its electrical, mechanical and chemical requirements, to any use thereof, for example, for cooling purposes in magnetic resonance tomographs nonmagnetic materials can be selected for the hollow body wall.

Besides the helium-filled hollow bodies 30, the regenerator housing may contain other heat-storing elements arranged in separate layers or mixed with the helium-filled hollow bodies 30, for example heat-storing elements made of rare earth alloys.

The invention has been described with reference to the preferred embodiments. Modifications and alterations may occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be constructed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.